# The Landsat Imagery of Southern Indian Lake: A Remote Perspective on Impoundment and Diversion

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by

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## ABSTRACT

Hecky, R.E. and G.K. McCullough. 1984. The Landsat imagery of Southern Indian Lake: a remote perspective on impoundment and diversion. Can. Tech. Rep. Fish. Aquat. Sci. 1266: iv + 20 p.

Seven colour Landsat images are reproduced, showing Southern Indian Lake from 1973, three years before impoundment, until the present. They provide a visual history of some of the major physical changes which have occurred in the lake. Increases in lake turbidity under high water conditions in 1975 and impoundment in 1976 which have been quantified with on-lake data are readily apparent in the imagery. The altered pattern of turbidity within the lake illustrates the nature of bank materials being eroded and circulation patterns of the lake. Black and white Landsat images provide direct evidence of the pattern of ice break-up on the lake and how it has changed with diversion. Newly flooded areas are readily apparent, as are dewatered lake areas on the lower Churchill River caused by river diversion. Satellite imagery can provide spatially extensive and continuous data on these large systems which are unavailable by any other means.


Key words: ice break-up; reservoir (water); satellite photography; satellite imagery; turbidity.


## RESUME

Hecky, R.E. and G.K. McCullough. 1984. The Landsat imagery of Southern Indian Lake: a remote perspective on impoundment and diversion. Can. Tech. Rep. Fish. Aquat. Sci. 1266: iv + 20 p.

Ce rapport comprend sept représentations couleurs Landsat du Lac sud des Indiens prises depuis 1973, soit trois ans avant la construction du barrage-réservoir. Elles constituent une histoire visuelle de quelques-uns des principaux changements physiques qui se sont produits dans le lac. On y voit nettement les augmentations dans la turbidité du lac, engendrées par la crue de 1975 et l'érection d'un barrage en 1976, qui ont été quantifiées à partir de données recueillies sur le lac. Les changements dans la turbidité du lac servent à déterminer la nature des matériaux arrachés aux rives ainsi que les schèmes de la circulation de l'eau dans le lac. Les représentations Landsat en noir et blanc illustrent clairement le processus de dégel du lac ainsi que les effets des ouvrages de dérivation sur ce dégel. On y voit distinctement les régions récemment inondées et les tronçons inférieurs du fleuve Churchill qui ont été mis à sec par les ouvrages de dérivation. Les images prises par satellite peuvent fournir des données continues sur de grand espaces à la fois à l'égard de ces systèmes étendus, qu'il serait impossible de se procurer autrement.


Mots-clés: débâcle; réservoir; photographie par satellite; turbidité.

## INTRODUCTION

Large lakes pose special problems to limnologists. Spatial variability becomes logistically difficult and expensive to characterize. Extensive travel is required to observed selected properties, and even to travel over the surface of large northern lakes is difficult or impossible during break-up or freeze-up without specially constructed ships or expensive air charters. Satellite imagery has opened new vistas for the study of large ecosystems. From its high orbit, a satellite can create instantaneous images of large sections of the earth surface. Because the lifetime of an earth observation satellite is from years to decades, it can create an historical record of images in a relatively standardized format. Satellite imagery, therefore, offers limnologists views of large lakes in which spatial and temporal variability over a lake's whole surface can be appreciated and analyzed.

The Landsat system which began in 1972 was one of the earliest earth observation systems from which data were available to the general public. The potential utility of Landsat imagery for monitoring aquatic systems was recognized soon after introduction. Most analytical interest has focussed on the multispectral scanner (MSS) which measures radiation in four spectral bands, 4 (500-600 nm), 5 (600-700 nm), 6 (700-800 nm) and 7 (800-1100 nm), and which yields useful information about aquatic systems. Bands 6 and particularly 7, covering the near infra-red spectrum, give very strong contrast between land and water because these surfaces have different infra-red absorption characteristics. Consequently these bands are ideal for measuring and monitoring water surface area on large aquatic systems (e.g. Currey 1977). Bands 4 and 5 in the visible spectral range image near surface water, and they have served as relative or absolute (with some on-water observations) measures of suspended sediment conditions (Amos and Alfoldi 1979; Aranuvachapun and LeBlond 1982).

Southern Indian Lake (SIL) in northern Manitoba (lat. 57°N, long. 99°WPM) was a large lake (1977 $km^2$) before impoundment in 1976, when its surface area was increased by 414 $km^2$ and much of the riverine flow through the lake was diverted (Newbury et al. 1984). The lake has been sampled for several years before and after impoundment during open water at selected stations. However, even at the maximum on-lake sampling density, achieved once annually by Patalas and Salki (1984), a single station represented over 30 $km^2$. For much of the research on the lake, individual stations are assumed to be representative of hundreds of square kilometres.

For SIL, satellite imagery can allow assessment of spatial variability and representativeness of sampling. The Landsat system has produced a series of images of SIL before and after impoundment of the lake and diversion of the Churchill River. It has provided a visual history of SIL which illustrates many of the significant features and changes in the lake since the inception of the Landsat program. This standardized record of observation will be an important technique in monitoring the recovery of the lake-reservoir as the fidelity of the record has been established by on-lake observation and by comparison with low-level aerial photography. Examination of satellite imagery reveals changes in the spring break-up pattern of ice attributable to diversion. These changes are important to the lake's thermal regime but are directly observed only with the satellite imagery (Hecky 1984; Patalas and Salki 1984). The imagery also documents changes in turbidity of the lake caused by shoreline erosion (Newbury and McCullough 1984). Suspended solids concentrations have increased dramatically in the lake, and SIL now exports more sediment than it receives (Hecky and McCullough 1984).

## METHODS

The basic operational parameters of the Landsat satellite program have been described in several general remote sensing texts. Much of the following is based on Lillesand and Kiefer (1979).

All satellite images in this report are from Landsat 1 and Landsat 2. The satellites of the Landsat system were originally called Earth Resources Technology Satellites (ERTS). Landsat 1 (ERTS-1) was launched on 23 July 1972 and produced MSS imagery until January 1978. It was followed by Landsat 2 (ERTS-B), launched on 22 January 1975 and producing imagery for the period January 1975 to November 1979 and June 1980 to February 1982.

Satellites of the Landsat program maintain an altitude of 880 km to 940 km on a near polar orbital path. Successive orbits progress westward to give repeat coverage of each portion of the earth every 18 days. During the overlap period of image production by Landsats 1 and 2 (January 1975 to January 1978) repeat coverage was available on 9 day intervals. Overlap between images recorded on successive orbits over SIL is approximately 65%. SIL happens to be well centered on orbital path 37, frame 20. In addition, up to three-quarters of the lake is often recorded on orbital path 36, frame 20. Thus, occasionally, good coverage is available on successive days. However, cloud cover, forest fire smoke and haze, and sometimes image quality problems combine to limit good coverage to as few as two good images per open water season. Coverage during the winter period is much better because of clearer atmospheric conditions. Orbital designs are such that images are approximately sun-synchronous. Actual time of production of each image is recorded in the last 5 digits of the image identification number, expressed as hours, minutes, and tens of seconds Greenwich Mean Time. Times of imagery at SIL listed in Table 1 are reported as Central Standard Time and range from 10:17 CST to 11:14 CST.

Total image coverage is 185 km x 185 km. Resolution as a function of the scanning system of the MSS recorders is commonly considered to be limited to a pixel dimension of 56 m (horiz-

ontal, or east-west) by 79 m (vertical). Scales of reproduction in this paper are approximately 1:640,000 in Figs. 5, 6, and 8 and 1:1,000,000 in Figs. 3, 4, and 7. Images reproduced are uncorrected for distortion due to rotation of the earth in the period required to complete the scans for each image. This distortion is equivalent to about 3 km longitudinal displacement to the west for each 100 km in latitude to the south.

The digital data received for each band can be reproduced as a black and white print by projecting recorded brightnesses onto photographic film. Colour composite prints are produced by assigning a primary colour to each of three of the spectral bands recorded and superposing the brightness data on colour film. In the illustrations in this paper, band 4 (500-600 nm) is reproduced as blue, band 5 (600-700 nm) as green and either band 6 (700-800 nm) or band 7 (800-1100 nm) as red. Because differences in the quality of data received for each band varied from image to image, the authors selected for each figure the combination best illustrating sediment patterns in Southern Indian Lake. Because infra-red radiation is absorbed by water, but tends to be strongly reflected by healthy vegetation, inclusion of band 6 or 7 in the composited image helps to delineate waterbodies from the surrounding land. Because the visible light recorded in bands 4 and 5 is affected by sediment suspended in the water column, areas of greater sediment concentration appear lighter blue in the composite images. Clearer deep water which absorbs more light is reproduced as darker blues and black.

Absolute colour values and tone on Landsat images are not only a function of spectral reflectance at the earth's surface, but are also affected by variable atmospheric conditions, and by characteristics of the Landsat recording and reproduction techniques. The discussion which follows, of the satellite record of turbidity in Southern Indian Lake waters, is based primarily on a consideration of relative differences in the blue tones representing the lake surface in each image. The limnologic significance of differences in colour and tone among, as opposed to within, images may be roughly grouped by considering the colour and tone of smaller adjacent lakes not connected with the Churchill River and Diversion. Chagarlamudi et al. (1980) established that these smaller lakes had insignificant changes in spectral reflectance over time, and they developed a computer-driven technique for analysis of Landsat reflectance values stored digitally on computer-compatible tapes, which we describe.

Technical data for MSS satellite and aerial photographs reproduced in this report are listed in Table 1. All aerial photographs were exposed through blue-limiting filters on panchromatic film with a resulting image spectral reproduction range of about 400 nm to 700 nm.

SIL levels and Churchill River discharges at Leaf Rapids reported in Table 2 for the days of imagery are based on Water Survey of Canada (1969-1981) published data. Discharges at Missi Falls and on the Diversion Route are based on data supplied by Manitoba Hydro.

The dates of break-up were determined for Table 3 by calculation of the date at which the 40 day mean temperature rose to 5°C (McFadden 1965). This calculated date coincides well with the observed average date of break-up in the years since impoundment.

Since June 1976, a record of the wind has been maintained at the Department of Fisheries and Oceans Research Station near the community of South Indian Lake. For earlier images data was supplied by the Atmospheric Environment Service from their weather stations at Lynn Lake, 140 km west of SIL and at Thompson, 150 km southeast of SIL. Because wind records are partly dependent on recording site conditions, data were compared among all stations for four summer months of 1976. A ratio was determined for mean monthly wind speeds between the South Indian Lake record and that of each station. Data from Lynn Lake and Thompson were multiplied by these ratios to estimate values more comparable for all years reported in Table 3. Locations named in the text are identified in Fig. 1, a map of the Southern Indian Lake region.

## RESULTS AND DISCUSSION

### TIME AND SEQUENCE OF BREAK-UP

Break-up of SIL in 1976, prior to impoundment, began from open water leads which appeared on the 5 April image (Fig. 2, arrows at southern part of SIL) in region 2 (Fig. 1). This shallow, island rich area of region 2 was historically known to have unsafe winter ice, and Penner (1974) photographed open water there on 1 March 1973. The only other open water visible on the 5 April 1976 image (Fig. 2, arrows at outlet, northern SIL) was at the outflow at Missi Falls. Penner (1974) reported open water there on 1 March 1973 as well as at Opachuanau Rapids between regions 0 and 1. By 23 April 1976 the open water leads in region 2 and near Missi Falls had grown significantly larger and new leads were apparent on the image along the inflowing Churchill River, at Opachuanau Rapids and in the narrows between regions 2 and 3. By 20 May the open water areas in region 2 had grown and coalesced, and most of the region was ice-free. The open water areas along the inflowing Churchill and at Opachuanau Rapids had also coalesced and extended into region 1. Marginal melting around shallow South Bay (region 6, Fig. 1) was visible although a large area of land-fast ice occupied most of that region. The Churchill River below Missi Falls was largely clear of ice. Although regions 4 and 5 remained entirely ice covered, there was a substantial open water area in region 3 south of Long Point. By 29 May regions 0-3 and 5-7 were ice-free and only region 4 had a large central floe remaining.

Flow conditions as well as atmospheric conditions clearly affected the timing and sequence of break-up in the various regions of SIL. McFadden (1965) found that the date on which the 40 day running mean temperature exceeded 5°C was a reasonably accurate approximation of break-up dates for large northern Canadian lakes. Hecky (1984) used McFadden's

approximations to estimate season lengths for SIL. By this method the date of break-up on SIL in 1976 was predicted to be 26 May. On 20 May regions 4 and 5 were still ice-covered while the southern half of SIL was ice-free (Fig. 2). The agreement with the evidence of Landsat imagery supports the use of McFadden's relationship for a mean date for the lake. Region 6 was the shallowest lake region before impoundment (mean depth = 4 m) and had the warmest under-ice water temperatures (Hecky 1984). Higher under-ice water temperatures tend to minimize growth of ice cover thickness. If atmospheric inputs alone determined break-up, region 6 would have been expected to thaw before other regions (Ragotzkie 1978). Because of higher flows passing through it, region 2 (mean depth = 8 m) began to thaw before region 6 . In areas of channel constriction such as the island-rich area of region 2 and the shallow strait south of Long Point, high flows resulted in relatively high current velocities which destratified the water column. These higher velocities suppressed ice growth by the processes of destabilization of the water column and advection of heat supplied by the flow (Stigebrandt 1978). In the extreme condition open water could have persisted all winter, but in less extreme situations, as in 1976, a thin ice cover formed. Once a lead formed in the spring, the changed albedo of the open water allowed higher absorption of radiant energy, which was sensed by the satellite as decreased reflected energy. These open water warming cells expanded by thermal erosion of the ice sheet primarily in the downstream direction as absorbed heat was advected away.

Diversion of the Churchill River through South Bay (Newbury et al. 1984) altered the break-up pattern of the lake. For example, the spring seasons of 1974 and 1979 were meteorologically similar, with calculated break-up dates of 7 June and 10 June, respectively. Available Landsat images from other years before and after impoundment show patterns of break-up similar to those visible in the 1974 and 1979 images (Fig. 3). Comparison of the Landsat images of 1974 and 1979 illustrate that the open water leads which had extended through regions 2 and 3 before diversion shifted to the south with diverted flows into and out of South Bay. Hecky (1984) and Patalas and Salki (1984) found that SIL regions 2, 3, 4, and 5 north of the diversion point have been 1°C to 2°C cooler at their maximum temperatures since diversion. Hecky (1984) concluded that the maximum temperatures achieved in the regions were in part related to the time of break-up. The loss of flow and the lack of open water leads to the north (Fig. 3B) delayed break-up and reduced the length of the heating season for the northern regions of the lake.

## SUMMER TURBIDITY AND FLOW PATTERNS

A sample of Landsat images of SIL taken during the open water periods of 1973-1980 (Fig. 4 to 7) illustrate the transition of SIL from a relatively clear lake in which the Churchill River was the major sediment source to a highly turbid lake where shoreline erosion was the major sediment source (Hecky and McCullough 1984).

The pre-impoundment image of 29 July 1973 (Fig. 5) shows some turbid areas (light blue to white tones) in shallow, marginal bays including, for example, Wupaw Bay, Bay 1 and the shallow bays at the east end of South Bay (Fig. 1). Turbidity in these areas was due to resuspension of bottom sediments and, on the eastern side of South Bay, some shoreline erosion. Cleugh (1974a) reported Secchi disc depths of 0.3 m to 0.4 m for Swan Bay and 0.4 m for Wupaw Bay in 1972 while adjacent regions had Secchi disc depths of 1 to 2 m. The inflowing Churchill River appears slightly more turbid than the outflowing river at Missi Falls. On 18 July 1973, Cleugh (1974b) reported total suspended sediment concentrations of 9 $mg \cdot L^{-1}$ for the inflowing river and 3 $mg \cdot L^{-1}$ for the outflow at Missi Falls. On this Landsat image, regions 4 and 5 were indistinguishable in their reflected radiances, and Cleugh (1974a) reported that they had similar Secchi disc visibilities. Initial construction activities are evident from bright white tones indicating road clearings around Missi Falls and clearing along the diversion route to and from Issett Lake.

Landsat imagery in 1976 (Fig. 4) shows the effects of impoundment on the lake. Discharges at Missi Rapids were reduced and diversion flow at South Bay was initiated in June 1976. By 31 July 1976 (Fig. 4A) the lake level had just exceeded the historic high as the water level was raised to initiate the diversion (Table 2). General turbidity levels in the regions south of Long Point are higher than in 1973 (Fig. 5), with South Bay clearly showing the earliest response in terms of turbidity increase, to the rising lake level. The diverted plume of the Churchill River entered South Bay relatively clear and left via the diversion channel highly turbid. The Churchill River flow entering regions 0 and 1 was also clear relative to other waters in the basins. By 4 September 1976 (Fig. 4B) the water level had increased by another 0.8 m to 257.8 m above MSL, within the controlled post-impoundment range. All regions of the lake were substantially more turbid. Hecky (1984) noted a dramatic increase in suspended sediment concentrations in the latter part of August 1976, for example: from 8.5 to 15 $mg \cdot L^{-1}$ in region 1 and from 1.5 to 7 $mg \cdot L^{-1}$ in region 4 (Hecky et al. 1979). Only regions 5 and 7 in SIL showed no change in turbidity with flooding (Fig. 5; Hecky 1984; Patalas and Salki 1984). Region 5 had predominantly sandy backshore deposits from which eroded material was rapidly deposited. Region 7 had very small fetches and a high proportion of steep bedrock backshore. All the other regions had lacustrine silty clay shorelines after flooding which rapidly eroded, causing increased suspended sediment concentration in the lake (Hecky and McCullough 1984). The turbid river flow leaving South Bay had extended farther into the Notigi Reservoir by September due to the increased flow since July.

Landsat images from 1978 and 1979 (Figs. 6 and 7) that depict SIL after full impoundment and diversion (Table 2) give similar general impressions but differ in detail. Both images show that the inflowing Churchill River was low in turbidity while the outflows at Missi Falls

and the Diversion Route carried higher suspended sediment loads. The impoundment of SIL had changed the lake from a basin of net sedimentation to one which exported sediment (Hecky and McCullough 1984). Regions 0-4 and 6 were very turbid while regions 5 and 7 had low turbidities which were unchanged from their pre-impoundment levels (Hecky 1984; Patalas and Salki 1984). The images together show that the post-impoundment conditions were similar year-to-year and that there was no tendency to return to the pre-impoundment condition within three years of the initial impoundment.

Figure 6 is an exceptionally bright image on which mixing processes between and within basins can be followed using the suspended sediment as a natural water mass tracer. The Churchill River entered SIL as a clear, dark plume. Total suspended sediment in the Churchill River water (5 mg $L^{-1}$, Cory Anema, Canada Dept. of Fisheries and Oceans, Winnipeg, pers. comm.) was similar to that in July 1973 (Fig. 5). Sediments were being added by shoreline erosion in regions 0 and 1. The dark plume appears to divide around the first large island in region 1. A spiralling dark stream to the south of the island contrasts with sediment laden water in the southern half of region 1. The northern margin of region 1 appears quite clear on this image but turbid water could penetrate into these regions (Fig. 7). Regions 2 and 3 appear less turbid than 1, 4 or 6, in the 1978 image (Fig. 6). Water transported by the river flow into regions 4 and 6 is evident as dark blue masses (Fig. 6) extending from regions 3 and 2, respectively. These plumes extend far into regions 4 and 6, in a jet-like structure which mixed only slightly with the remaining water in the basins.

The 1979 image (Fig. 7) was acquired much later in the open water season than the 1978 image (August 1979 compared with June 1978), and the turbidity in regions 1, 2, 3 and 6 appears much more uniform than in the June 1978 image (Fig. 6). Hecky and McCullough (1984) observed that regions 1, 2 and 6 were well-flushed by the Churchill River during the ice covered period and the initial sediment concentrations after break-up were essentially indistinguishable from the inflowing Churchill River. As shoreline erosion proceeded after break-up, sediments were added to the lake waters faster than they were removed by outflow and sedimentation and concentrations of sediments increased. Intra-regional variability in sediment concentration would have been more extreme in June in the rapidly flushed areas than in the autumn as comparison of the 1978 and 1979 images shows. Figures 6 and 7 also emphasize how the turbid plume (light blue tones) leaving the South Bay diversion channel did not mix with marginal back-flooded areas (dark blue-black tones) in the upper Notigi Reservoir.

Marginal bays in SIL often had quite different turbidity levels than the large, open basins. Good examples are Wupaw Bay and Bay 1 (Fig. 1). Prior to impoundment these bays were quite shallow. As wind-generated waves resuspended sediments from their bottom deposits, these shallow bays were more turbid than the large basins they adjoined (Fig. 5). With increased water level (Wupaw Bay mean depth increased from 2.1 m to 4.5 m) less wind stress was transferred to the bay's bottom deposits and resuspension decreased. In Fig. 6, after impoundment, Wupaw Bay and Bay 1 appear less turbid than their neighbouring, open basins where shoreline erosion was much more intense due to the larger fetches. Comparison of low level aerial photography (Fig. 9) also illustrates this effect. Secchi disc values within Wupaw Bay after impoundment ranged from 1.0 m to 1.4 m (Hecky et al. 1979) substantially higher than the 0.4 m observed before impoundment (Cleugh 1974a). The 1978 aerial photography of Wupaw Bay (Table 1; Fig. 9) was taken two hours before the Landsat image in Fig. 6. This fortuitous circumstance substantiated the Landsat image at a much larger scale. Other aerial photography of the Loon Narrows area (Fig. 10) taken within two hours of the Landsat image shows the structure of mixing turbid and non-turbid waters in greater detail, and corroborates the fidelity of the Landsat image (compare with Fig. 6). A complex example of water mass mixing using sediment from an eroding shoreline as a tracer is illustrated by an aerial photograph (Fig. 11) taken in the southern half of region 4 (area 4A in Fig. 1) in 1977. All manner of water mass structures from straight line fronts to complex gyres were present in a 50 $km^2$ area.

Digital analysis of computer compatible tapes of Landsat data can make analysis of spatial variability rapid and quantitative within temporal limits set by orbital repeat intervals and cloud cover. An example is offered in Fig. 12 where a portion of the 30 July 1976 image (area 6A, Fig. 1) has been digitally processed. The region chosen for illustration shows a large range of brightness values in a relatively small area. Each symbol in Fig. 12 represents a 56 x 79 m area, the limit of spatial resolution on Landsat 1. The brightness of each pixel has been assigned a Secchi disc value interval based on a correlation derived by Chagarlamudi et al. (1980) for the relationship between quantitative brightness received by the satellite and on-lake observations of Secchi disc depths. From examination of Fig. 11 it is obvious that considerable care must be taken when on-lake sampling is used to calibrate aerial or satellite imagery for suspended sediment studies. For 11 data pairs with Secchi depths ranging from 0.3 m to 4 m, the correlation coefficient was -0.951. Through this procedure, complex spatial variability can be analyzed and integrated over an area of interest to define realistic mean values. The procedure allows extensive extrapolation of relatively few point-source data, and it gives limnologists a unique analytical tool which is especially valuable on large systems.

## REDUCED FLOWS AND WATER LEVELS ON THE LOWER CHURCHILL RIVER

The diversion of the Churchill River in 1976 greatly reduced flows in the lower Churchill below Missi Falls. As levels on the lakes on the lower Churchill were flow controlled, reduction of flow led to dramatically falling

lake levels (Brown 1974), reducing the water areas, and exposing large areas of lake bed. Water areas on Partridge Breast Lake and Northern Indian Lake (Fig. 1) have been reduced by 40% and more under extreme low flows (Brown 1974). In Fig. 8 two Landsat views of the lower Churchill under natural (A) and diversion (B) discharge conditions (Table 2) illustrate the reduction in water areas. The bright white lake outlines are due to high reflected radiance from exposed lake bottom. Landsat RBV and MSS data were used by Jaques (1983) to measure changes in shoreline ecotones along lower Churchill River lakes. Radiometric (brightness) values were found to vary significantly on one or both of bands 5 and 7 for 5 types of lake bottom shown exposed on the 22 September 1981 image. They were, for instance, able to discriminate between dry sand flats and wetter clays and silts, and to identify the extent of new vegetation growth on the recently exposed lake bottom. Continued monitoring of the degree and rate of encroachment of plant communities onto the exposed flats can be accomplished using periodically acquired Landsat MSS data.

Jaques (1983) also mapped changes in the number and size of islands from Landsat. Lowering of the level of Northern Indian Lake reduced the total number of islands from 179 to 77. Aerial and ground surveys indicated that Canada geese did not use islands larger than 14 ha for nesting. The combined effect of islands becoming connected to each other and the mainland, and the general increase in size reduced suitable nesting islands from 149 to only 35 (Jaques 1983). One can see in Fig. 8B that, by the similar process of exposing a former underwater bay-mouth bar, Partridge Breast Lake has been split into 2 parts due to lowered lake level. The westernmost basin continued to receive highly turbid water from the SIL discharge at Missi Rapids while the southeastern lobe of the lake became isolated and had very low turbidity.

## CONCLUSION

Satellite imagery of inland waters offers the potential to observe large aquatic systems in a manner previously impossible. The ability of the satellite observation system to monitor on large reservoirs the flooded and dewatered areas (and by difference the zone affected by drawdown) make satellite image analysis an important tool in reservoir management. Satellite imagery on SIL has established that a change in the break-up pattern of the lake occurred with diversion of the Churchill River. This change could only be inferred from on-lake observations (Hecky 1984) as acquisition of such information by other means was logistically impossible (boat travel) or prohibitively expensive (aerial surveys). Changes, because of turbidity, in lake surface reflectance evident to satellites have been validated by on-lake observations both qualitatively and quantitatively (Chagarlamudi et al. 1980). Although satellite imagery shows fine scale spatial variability in turbidity not observed in routine sampling, the gross regional changes in turbidity recorded by on-lake observation at one or several stations in a region are representative of trends occurring over entire regions. Because Landsat imagery has provided a faithful and interpretable record of changes in SIL through time, it can be used to monitor the recovery of the lake to natural turbidity levels as shoreline erosion subsides. It can replace costly on-lake observations which are spatially and temporally infrequent, providing improved resolution at reduced costs. Satellite acquired imagery has already been applied to several reservoirs (Gupta and Bodechtel 1982; Chagarlamudi et al. 1980; Abiodun and Adeniji 1978; Ritchie et al. 1977). If fisheries scientists are able to develop critical physical habitat parameters, as Jaques (1983) has done for Canada geese in the dewatered Lower Churchill River, satellite monitoring will become an even more useful habitat assessment tool for the aquatic environment.

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## REFERENCES

ABIODUN, A.A. and H.A. ADENIJI. 1978. Movement of water columns in Lake Kainji. Remote Sens. Environ. 7: 227-234.

AMOS, C.L. and T.T. ALFOLDI. 1979. The determination of suspended sediment concentration in a macrotidal system using Landsat data. J. Sediment.Petrol. 49: 159-173.

ARANUVACHAPUN, S. and P.H. LeBLOND. 1982. Turbidity of coastal water determined from Landsat. Remote Sens. Environ. 11: 113-132.

BROWN, S.B. 1974. The morphometry of Rat-Burntwood diversion route and lower Churchill lakes: present conditions and post-regulation conditions. L. Winnipeg, Churchill and Nelson R. Study Bd, 1971-75, Tech. Rep. Appendix 5, V.2, Rep. D: 51 p.

CHAGARLAMUDI, P., R.E. HECKY and J.S. SCHUBERT. 1980. Quantitative monitoring of sediment levels in freshwater lakes from Landsat, p. 115-118. In V.V. Salomonson and P.D. Bhavsar (ed.) The contribution of space observations to water resources management. Pergamon, New York.

CLEUGH, T.R. 1974a. The hydrography of Southern Indian Lake: present conditions and implications of hydroelectric development. L. Winnipeg, Churchill and Nelson R. Study Bd, 1971-75, Tech. Rep. Appendix 5, V.1, Rep. C: 195 p.

CLEUGH, T.R. 1974b. Hydrographic survey of lakes on the lower Churchill and Rat-Burntwood Rivers and reservoirs and lakes

of the Nelson River lakes and reservoirs. L. Winnipeg, Churchill and Nelson R. Study Bd, 1971-75. Tech. Rep. Appendix 5, V. 2, Rep. E: 230 p.

CURREY, D.T. 1977. Identifying flood water movement. Remote Sens. Environ. 6: 51-61.

GUPTA, R.P. and J. BODECHTEL. 1982. Geotechnical applications of Landsat image analysis of Bhakra Dam reservoir, India. Remote Sens. Environ. 12: 3-14.

HECKY, R.E. 1984. Thermal and optical characteristics of Southern Indian lake before, during and after impoundment and Churchill River diversion. Can. J. Fish. Aquat. Sci. 41(4): In press.

HECKY, R.E. and G.K. McCULLOUGH. 1984. The effect of impoundment and diversion on the sediment budget and nearshore sedimentation of Southern Indian Lake. Can. J. Fish. Aquat. Sci. 41(4): In press.

HECKY, R.E., J. ALDER, C. ANEMA, K. BURRIDGE and S.J. GUILDFORD. 1979. Physical data on Southern Indian Lake, 1974 through 1978, before and after Churchill River diversion (in two parts). Can. Fish. Mar. Serv. Data Rep. 158: iv + 523 p.

JAQUES, D.R. 1983. Evaluation of Landsat imagery for use in monitoring habitat change brought about by alteration of water regimes on the Churchill River, Manitoba. Report prepared for Canadian Wildlife Service, Edmonton, by Ecosat Geobotanical Surveys Inc. 63 p.

LILLESAND, T.M. and R.W. KIEFER. 1979. Remote sensing and image interpretation. John Wiley and Sons, New York.

McFADDEN, J.A. 1965. The interrelationship of lake ice and climate in central Canada. Tech. Rep. No. 20, No. 1202(07), Department of Meteorology, University of Wisconsin, Madison: 120 p.

NEWBURY, R.W., R.E. HECKY and G.K. McCULLOUGH. 1984. The Southern Indian Lake impoundment and Churchill River diversion. Can. J. Fish. Aquat. Sci. 41(4): In press.

NEWBURY, R.W. and G.K. McCULLOUGH. 1984. Shoreline erosion and re-stabilization in the Southern Indian Lake reservoir. Can. J. Fish. Aquat. Sci. 41(4): In press.

PATALAS, K. and A. SALKI. 1984. Effects of impoundment and diversion on the crustacean plankton of Southern Indian Lake. Can. J. Fish. Aquat. Sci. 41(4): In press.

PENNER, F. 1974. Anticipated effect of the Churchill River diversion project on the ice cover of Southern Indian Lake. L. Winnipeg, Churchill and Nelson R. Study Bd, 1971-75, Tech. Rep. Appendix 2, V. 1, Rep. F: 20 p.

RAGOTZKIE, R.A. 1978. Heat budgets of lakes, p. 1-19. In A. Lerman (ed.) Lakes: chemistry, geology, physics. Springer-Verlag, New York.

RITCHIE, J.C., F.R. SCHIEBE and J.R. McHENRY. 1977. Estimating suspended sediment loads from measurements of reflected solar radiation, p. 466-471. In H. Golterman (ed.) Interactions between sediments and fresh water. Junk, The Hague.

STIGEBRANDT, A. 1978. Dynamics of an ice-covered lake with through flow. Nord. Hydrol. 9: 219-244.

WATER SURVEY OF CANADA, ENVIRONMENT CANADA. 1969-1981. Surface water data: Manitoba.

Table 1. Technical data for satellite MSS (880-940 km altitude) and airborne photographic imagery.

| Figure number | Time (CST) | Date | Image identification | Aerial Photographs: Lens focal length (mm) | Aerial Photographs: Camera elevation above lake level (m) | Landsat images: MSS bands in illustration |
|---|---|---|---|---|---|---|
| 9A | 09:30 | 10 Aug 1969 | A21173-31 | 152.52 | 4880 | - |
| 5 | 11.14 | 29 Jul 1973 | 10371 17141 | - | - | 4, 5, 7 |
| 3A | 11:02 | 12 May 1974 | 10658 17024 | - | - | 6 |
| 8A | 11:02 | 17 Jun 1974 | 10694 17013 | - | - | 4, 5, 6 |
| 2 | 10:58 | 5 Apr 1976 | 20439 16583 | - | - | (6) not illustrated |
| 2 | 10:58 | 23 Apr 1976 | 20457 16580 | - | - | (6) not illustrated |
| 2 | 10:58 | 11 May 1976 | 20475 16573 | - | - | (6) not illustrated |
| 2 | 10:31 | 20 May 1976 | 11397 16310 | - | - | (6) not illustrated |
| 2 | 10:57 | 29 May 1976 | 20493 16570 | - | - | (6) not illustrated |
| 4A,12 | 10:26 | 31 Jul 1976 | 11469 16253 | - | - | 4, 5, 6 |
| 4B | 10:17 | 4 Sep 1976 | 11504 16165 | - | - | 4, 5, 6 |
| 11 | 07:00 | 16 Jul 1977 | A24737-185,7 | 152.46 | 7670 | - |
| 10 | 09:00 | 24 Jun 1978 | A24935-146,7,8 | 152.92 | 7670 | - |
| 9B | 09:30 | 24 Jun 1978 | A24936-7,8 | 152.92 | 7670 | - |
| 6 | 10:41 | 24 Jun 1978 | 21249 16410 | - | - | 4, 5, 7 |
| 3B | 10:54 | 14 May 1979 | 21573 16542 | - | - | 7 |
| 7 | 10:57 | 30 Aug 1979 | 21681 16571 | - | - | 4, 5, 7 |
| 8B | 10:59 | 1 Aug 1981 | 22383 16585 | - | - | 4, 5, 7 |

Table 2. Hydrologic data for dates of satellite MSS and airborne photographic imagery. "E" indicates an estimated value based on a correlation with downstream flows or Southern Indian lake water budget calculations. Such estimates should be considered only as approximate indicators of the proportions of flow through either outlet.

| Figure number | Date | Lake level at South Indian Lake community (m above MSL) | Discharges: Churchill R. at Leaf Rapids ($m^3 s^{-1}$) | Churchill R. at Missi Falls ($m^3 s^{-1}$) | Diversion route at South Bay ($m^3 s^{-1}$) |
|---|---|---|---|---|---|
| 9A | 10 Aug 1969 | 254.9 | 700E | 850E | 0 |
| 5 | 29 Jul 1973 | 255.3 | 1005 | 1050E | 0 |
| 3A | 12 May 1974 | 255.5 | 1147 | 1150E | 0 |
| 8A | 17 Jun 1974 | 256.1 | 1143 | 1300E | 0 |
| 2 | 5 Apr 1976 | 256.0 | 872 | 950E | 0 |
| 2 | 23 Apr 1976 | 255.8 | 895 | 950E | 0 |
| 2 | 11 May 1976 | 255.9 | 889 | 972 | 0 |
| 2 | 20 May 1976 | 256.0 | 886 | 999 | 0 |
| 2 | 29 May 1976 | 255.9 | 861 | 1445 | 0 |
| 4A | 31 Jul 1976 | 257.0 | 1283 | 367 | 124 |
| 4B | 4 Sep 1976 | 257.8 | 1322 | 620 | 350E |
| 11 | 16 Jul 1977 | 258.1 | 1546 | 1076 | 340 |
| 6,9B, 10 | 24 Jun 1978 | 258.1 | 1025 | 571 | 817 |
| 3B | 14 May 1979 | 257.7 | 933 | 175 | 764 |
| 7 | 30 Aug 1979 | 257.9 | 853 | 175 | 803 |
| 8B | 1 Aug 1981 | 257.7 | 747 | 34 | 912 |

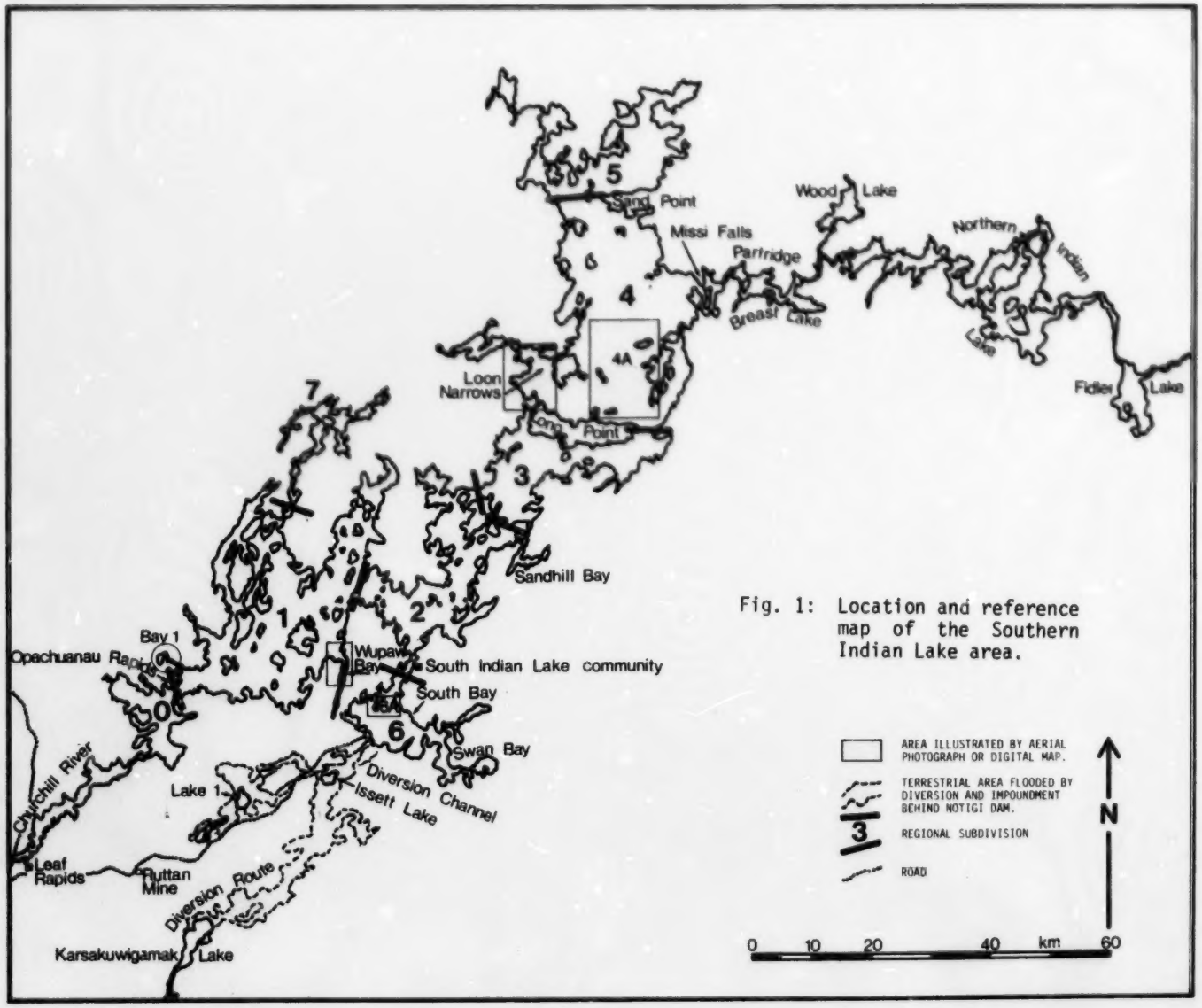



Fig. 1: Location and reference map of the Southern Indian Lake area.

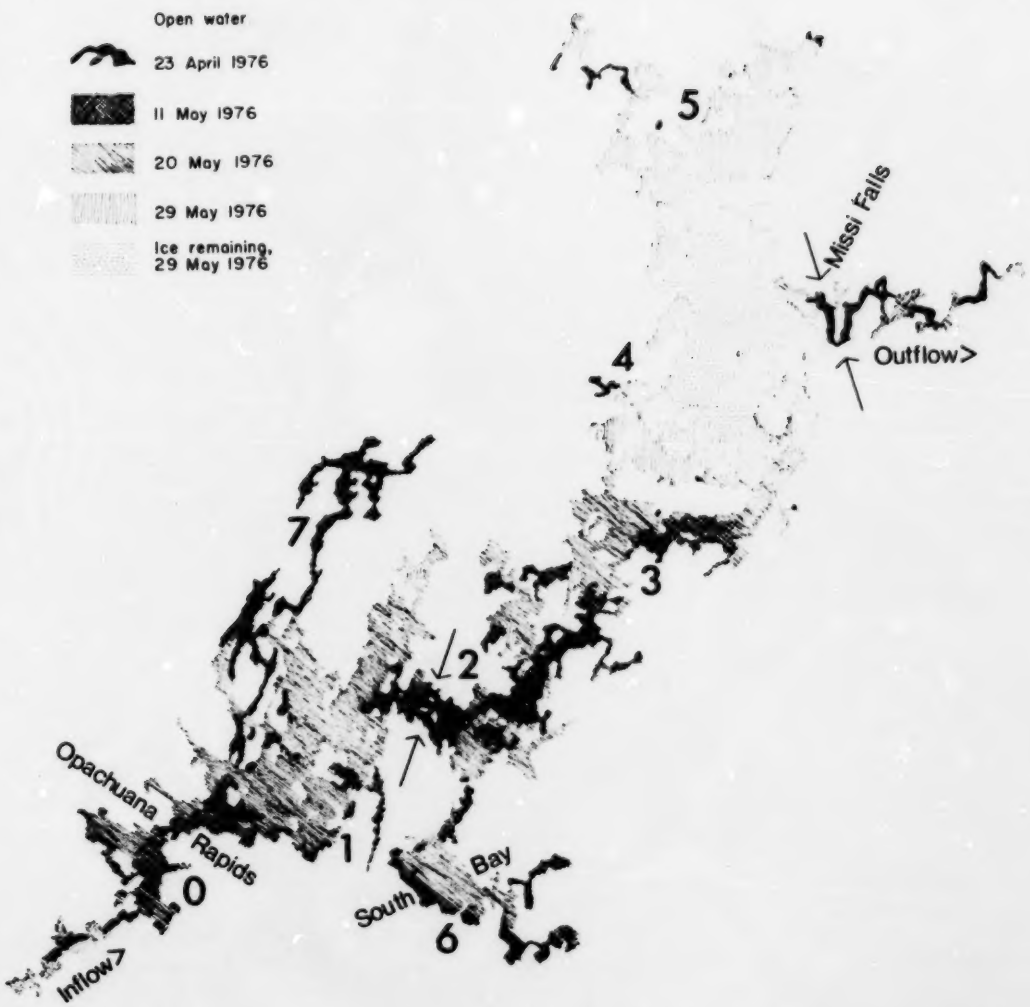



Fig. 2: Composite of open water areas visible on satellite images in the spring of 1976. Arrows indicate locations of small open water areas visible on imagery of 5 April 1976.

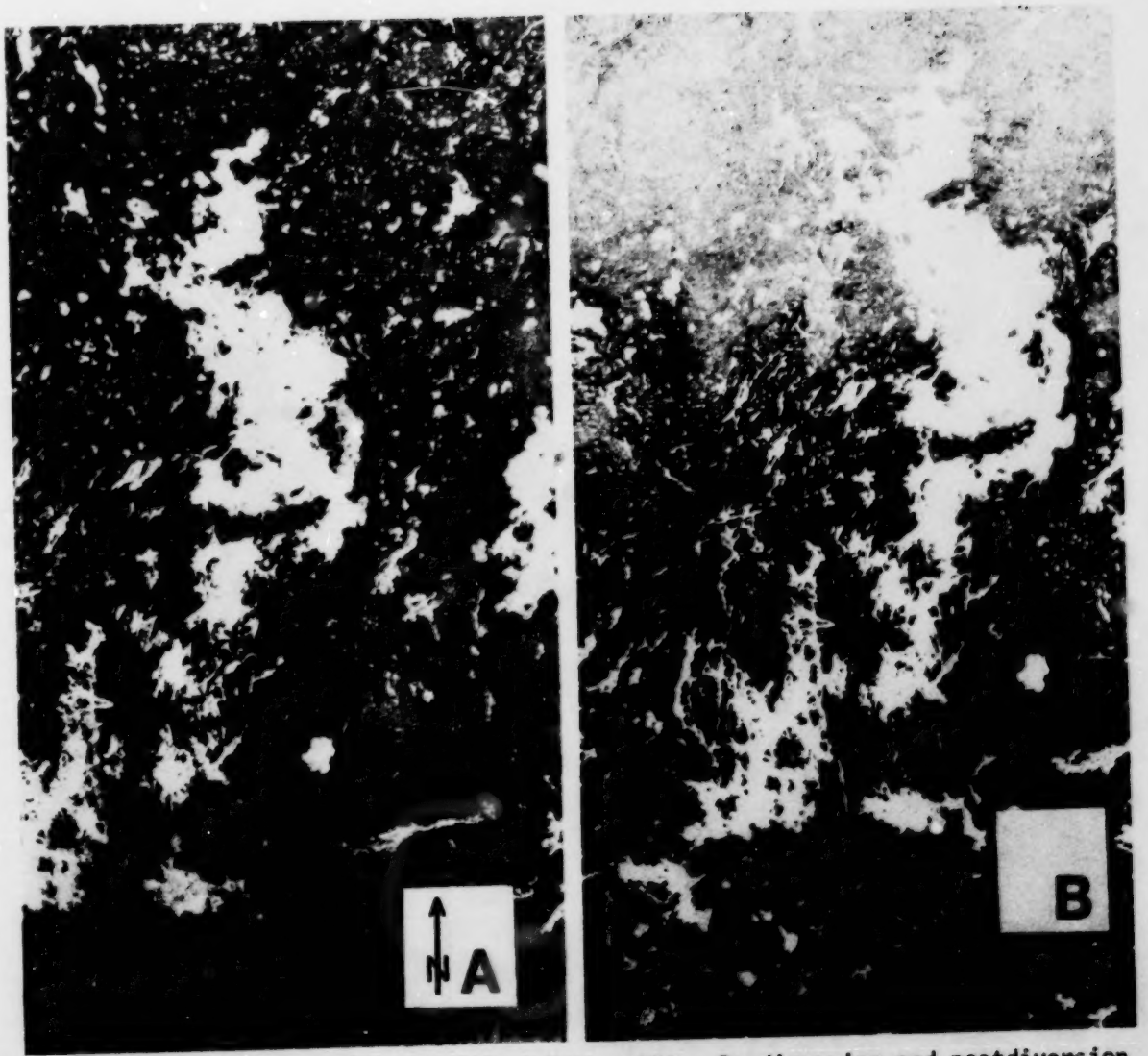



Fig. 3: (A) 12 May 1974 and (B) 14 May 1979. Prediversion and postdiversion images of SIL during the early ice break-up period.

Table 3. Pertinent meteorological data for satellite MSS and airborne photographic imagery.

| Figure number | Date | Period after ice-out (d) | Weather station[a] | Mean speed in week preceding date of imagery (km $h^{-1}$) | Prevailing direction and mean daily wind speed (km $h^{-1}$) number of days before date of imagery: 7 | 6 | 5 | 4 | 3 | 2 | 1 | Prevailing direction[b] and mean wind speed for 6 h preceding time of imagery (km $h^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 29 Jul 1973 | 62 | LL | 5.9 | SW 10.1 | S 7.7 | S 3.2 | E 4.1 | SE 8.5 | SE 6.2 | N 4.4 | NE(0.7) 9.9 |
| | | | Th | 9.2 | SW 12.3 | S 9.0 | N 3.4 | E 12.4 | E 14.0 | N 3.9 | W 9.3 | NE(0.3) 12.2 |
| 8A | 17 Jun 1974 | 10 | LL | 8.3 | N 9.0 | N 8.6 | SE 6.3 | SE 10.1 | N 10.2 | N 6.2 | SE 9.2 | SE(0.8) 12.8 |
| | | | Th | 14.2 | N 15.4 | N 18.2 | N 10.4 | E 16.1 | NE 17.8 | NE 12.0 | E 9.1 | E(0.6) 8.0 |
| 4A | 31 Jul 1976 | 66 | SIL | 10.3 | SW 6.4 | NW 5.2 | SE 9.6 | SE 20.0 | SE 16.3 | NE 10.0 | NE 4.9 | NW(0.5) 5.6 |
| 4B | 4 Sep 1976 | 101 | SIL | 7.2 | NW 6.9 | SE 6.3 | NE 7.2 | NW 6.6 | NW 5.7 | SE 11.6 | SE 6.0 | SW(0.7) 3.5 |
| 11 | 16 Jul 1977 | 65 | SIL | 8.5 | SE 8.0 | S 2.3 | NE 7.6 | SE 9.6 | NW 13.7 | SW 7.8 | NW 10.4 | NE(0.3) 1.3 |
| 6, 10 | 24 Jun 1978 | 24 | SIL | 11.3 | NW 16.9 | NW 12.5 | NW 9.2 | SW 9.1 | NE 12.0 | NE 9.6 | NE 9.9 | SE(1.0) 7.5 |
| 7 | 30 Aug 1979 | 81 | SIL | 8.1 | SW 5.0 | NW 8.8 | NW 8.0 | NW 6.0 | SW 6.5 | NW 8.6 | NW 13.5 | NW(0.7) 7.0 |
| 8B | 1 Aug 1981 | 59 | SIL | 7.6 | NW 10.1 | NW 6.6 | SW 6.4 | SW 6.4 | (NE) 9.7 | (SE) 7.0 | (NE) 6.8 | S(0.7) 4.0 |

[a] LL = Lynn Lake Th = Thompson SIL = South Indian Lake.

[b] Number in parentheses following prevailing direction is fraction of total 6 h period in which wind was from prevailing direction.

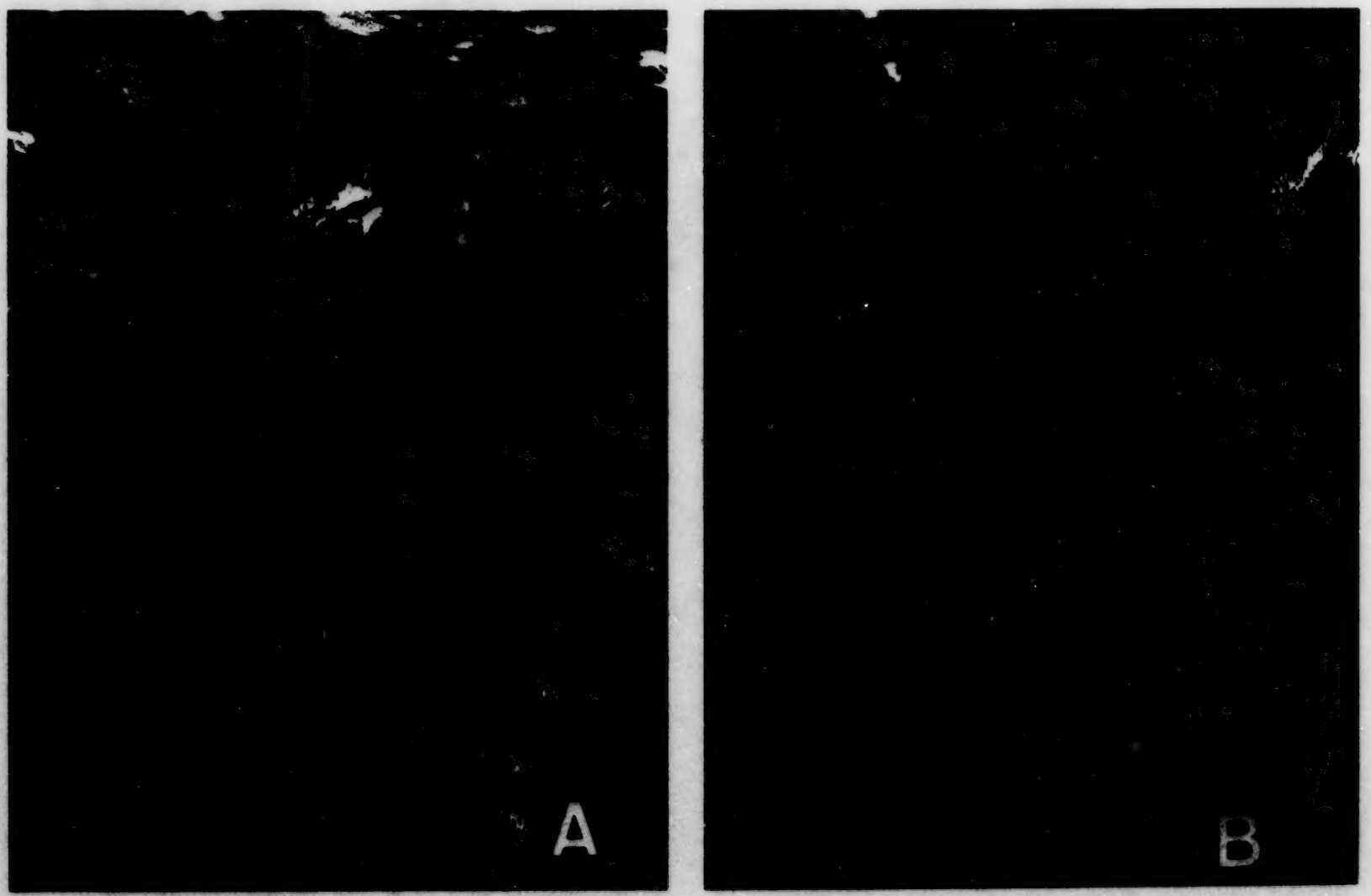



Fig. 4: (A) 31 July 1976, and (B) 4 September 1976. Images of SIL during impoundment, with partial diversion.

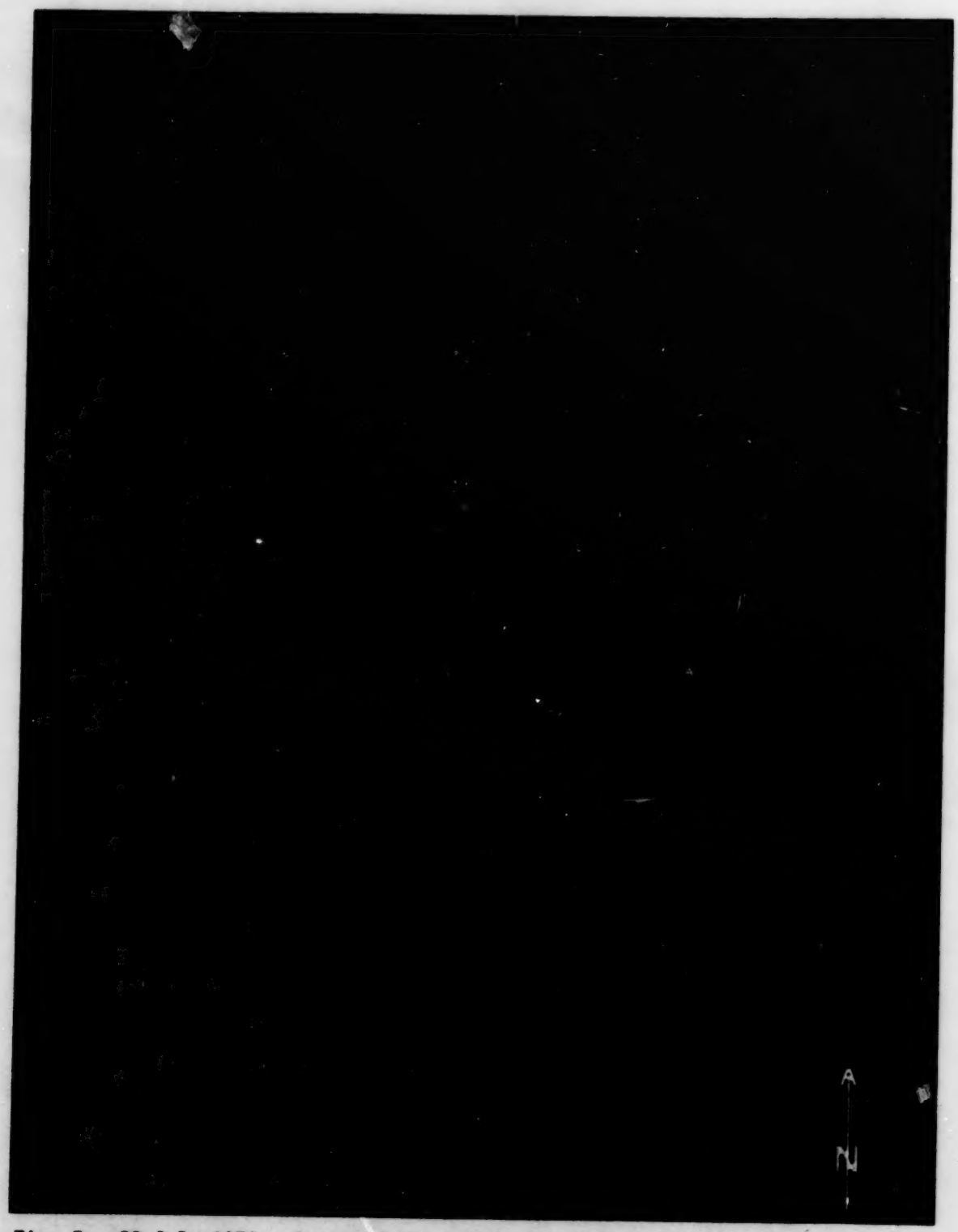



Fig. 5: 29 July 1973. Image of SIL before impoundment or diversion.

Fig. 6: 24 June 1978. Image of SIL after impoundment and with full diversion.

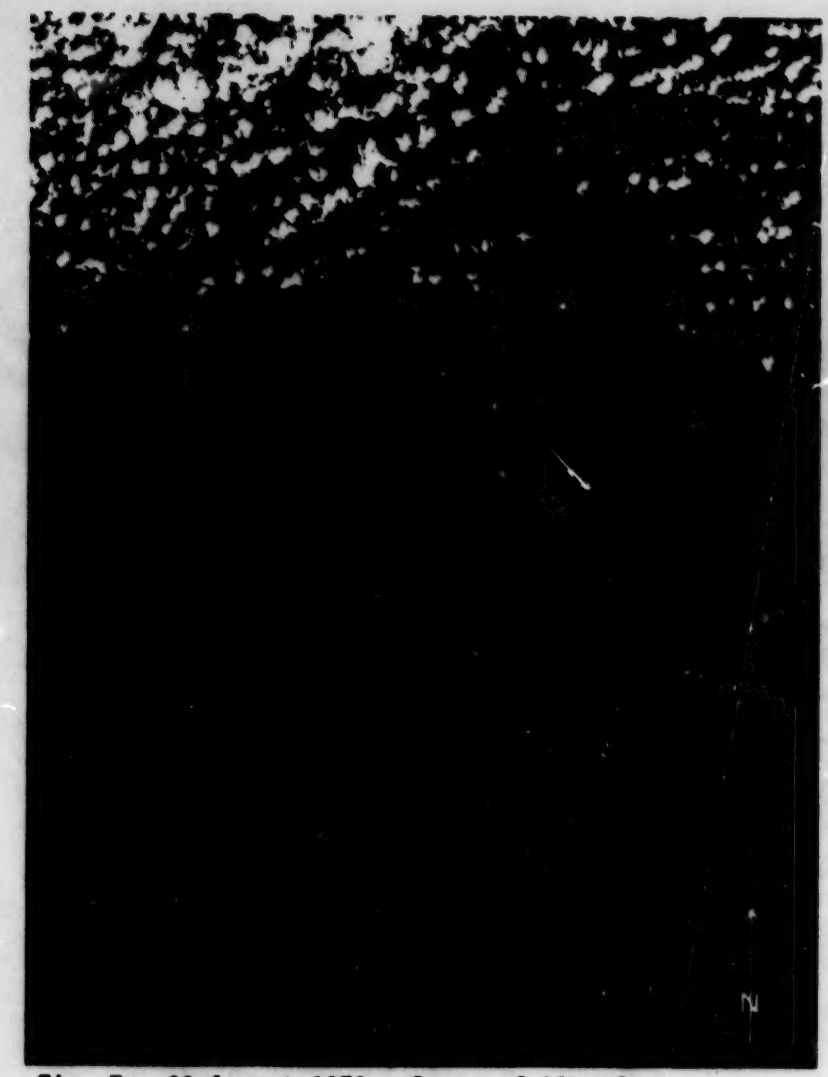


Fig. 7: 30 August 1979. Image of SIL after impoundment, and with full diversion.

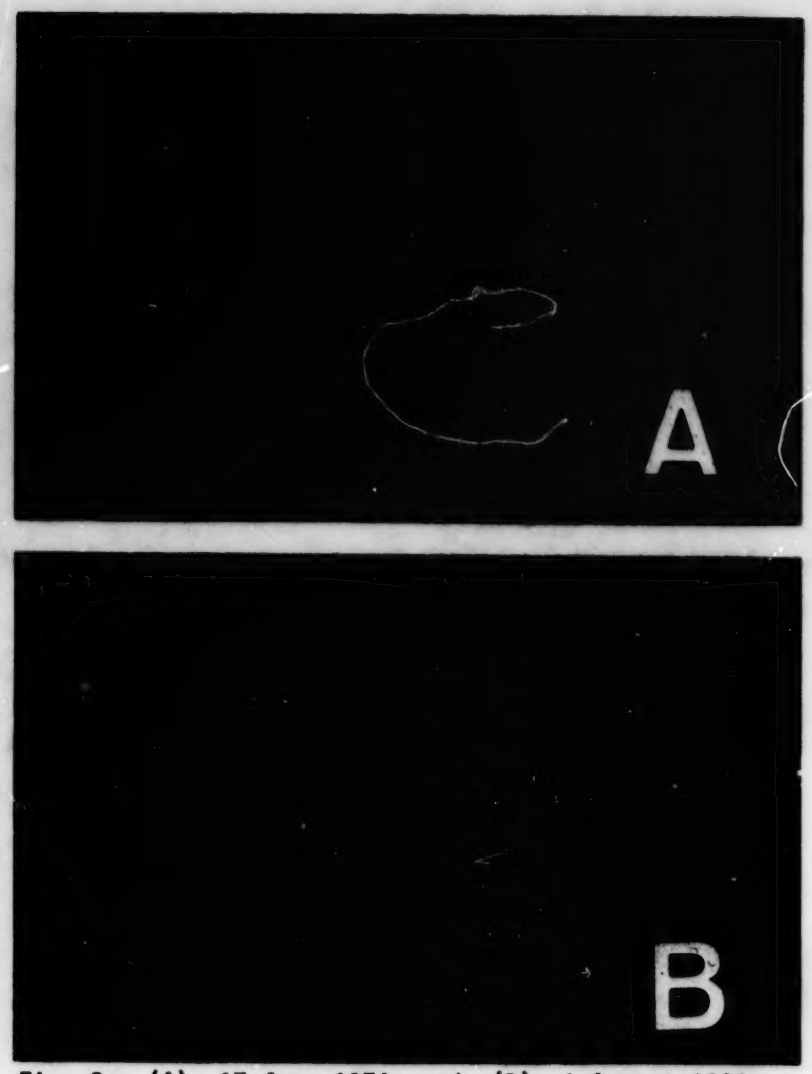



Fig. 8: (A) 17 June 1974, and (B) 1 August 1981. Pre- and postdiversion images of the lower Churchill River. White borders around lakes in B are due to high reflectance of vegetation-free, abandoned shorelines.

Fig. 9: (A) 1969, and (B) 1978. Aerial views of Wupaw Bay before and after impoundment.

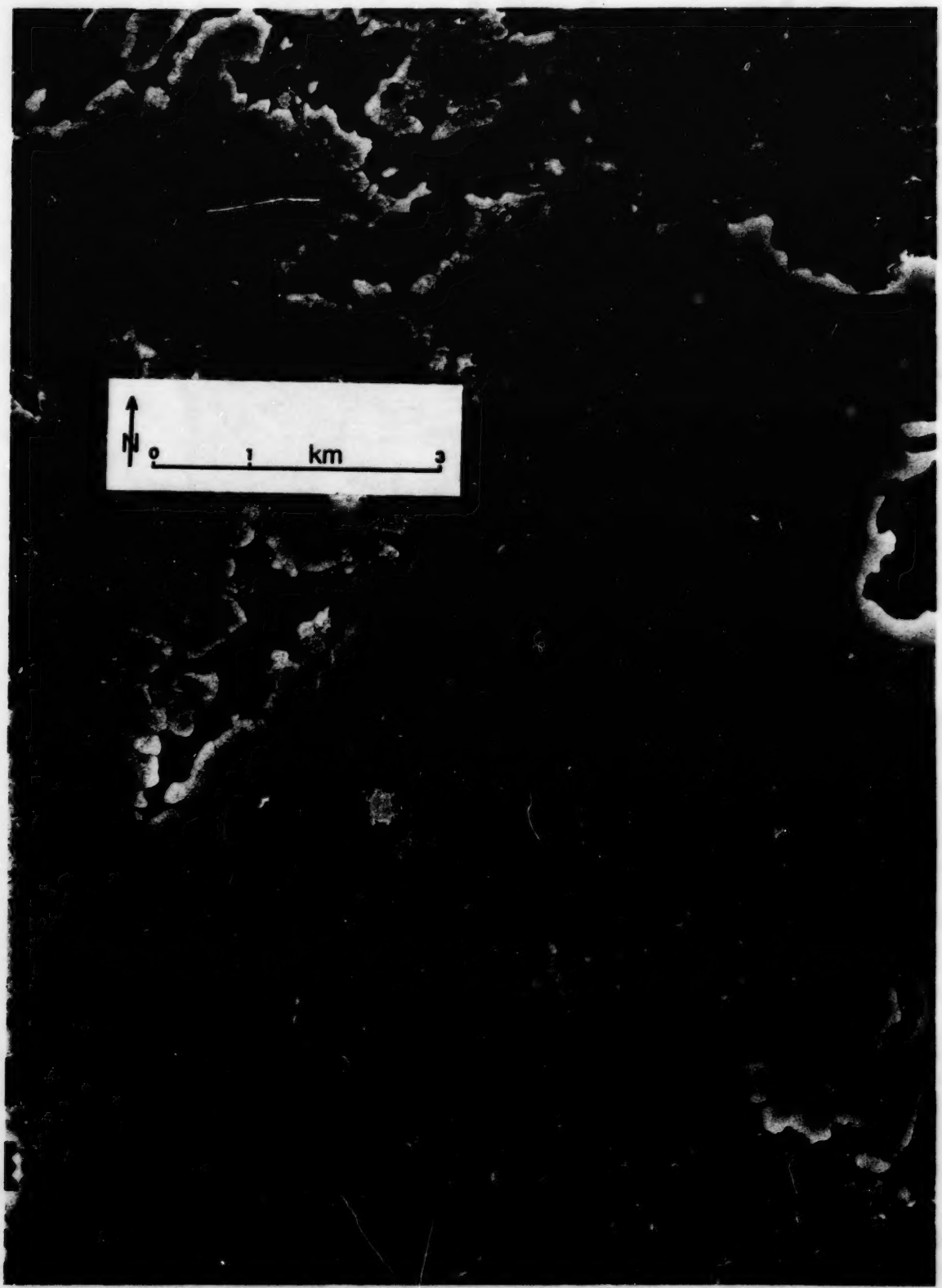



Fig. 10: Aerial photograph of Loon Narrows area taken less than two hours before Landsat image in Fig. 6.

Fig. 11: Aerial photograph taken in 1977 of area 4A (see Fig. 1) illustrating the complexity of water mass mixing.

| Map Symbol | Secchi Disc Depth (m) |
|---|---|
| 2 | 1.5 - 2.2 |
| 3 | 1.0 - 1.5 |
| 4 | 0.7 - 1.0 |
| 5 | 0.5 - 0.7 |
| 6 | 0.3 - 0.5 |
| 7 | 0.2 - 0.3 |
| 8 | 0.1 - 0.2 |
| 9 | 0.0 - 0.1 |

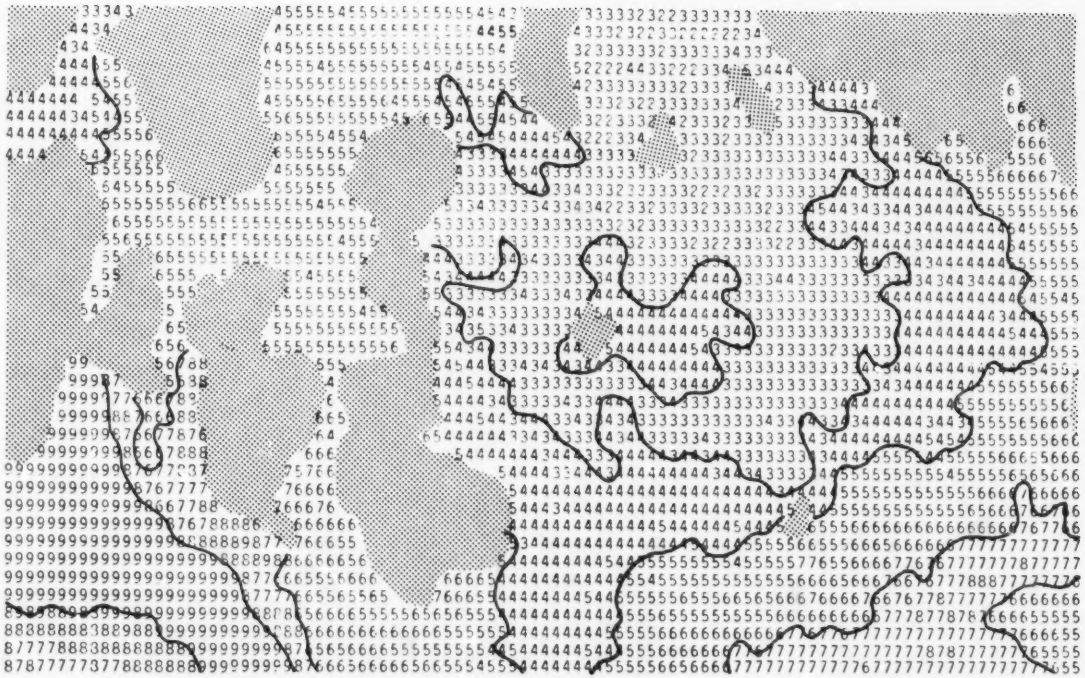
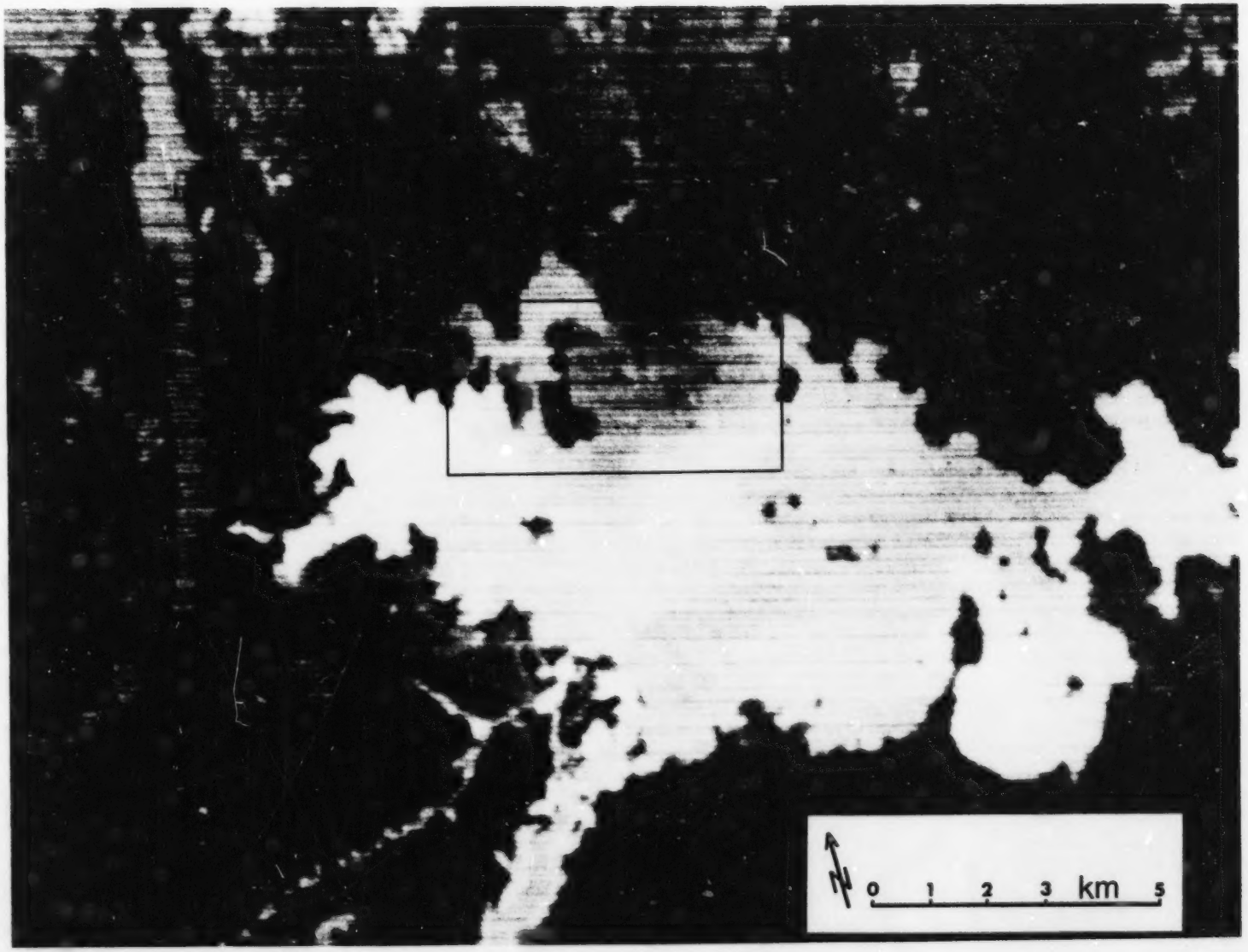


Fig. 12: Water classification map of a portion of South Bay (area 6A, Fig.1) based on digital processing of the Landsat image of 31 July 1976, and established correlations between Secchi disc values and satellite signals (Chagarlamudi et al. 1980). The location of the digital water classification map is indicated by the rectangle on the enlarged Landsat image (facing page). Lines on map are generalized contours intended only to aid the eye in discriminating areas of approximately equal Secchi depth.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